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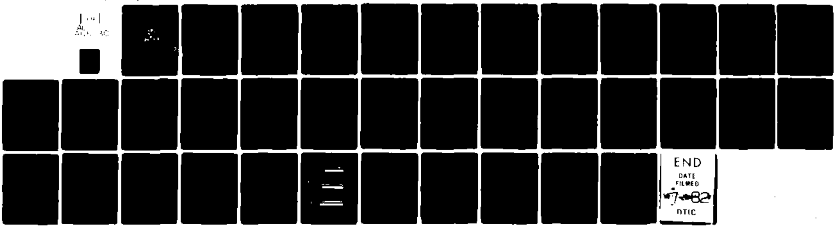

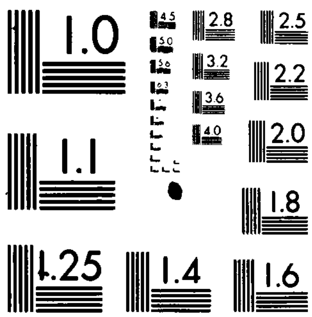

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CATEGORY AND WORD SEARCH: GENERALIZING SEARCH PRINCIPLES TO COMPLEX PROCESSING

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REPORT HARL-ONR-8103

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Category and Word Search: Generalizing Search Principles to Complex Processing

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Abstract

The research examines how the major phenomena in simple visual search generalize to searching for words and categories of words. Seven prominent effects in the visual search literature are reviewed. Experiment 1 examined word and category visual search when the targets and distractor sets had a varied mappping (VM) across trials. Reaction time was a linear function of the number of comparisons with a positive slope of 48 msec per word, 92 msec per category. Results suggest self-terminating search with reaction time being a linear function of memory and display comparisons with little or no improvement with practice. Experiment 2 examined search with a consistent mapping (CM) between targets and distractors. Category search slope dropped to 2 msec and became nonlinear. Word search slope dropped to 18 msec but was still linear. Experiment 3 examined simultaneous category detection and a concurrent serial recall digit-span task. Subjects could simultaneously perform the digit-span task and CM category search without deficit. However, combining VM category search and the digit-span task resulted in substantial performance deficit. The generality of effects across stimulus complexity levels and four principles of search processing are discussed with regard to automatic/control processing theory and production systems.

Category and Word Search: Generalizing Search Principles to Complex Processing

For over a decade the visual search paradigm (e.g., Sternberg, 1966) has been used intensively to investigate research questions associated with the detection of relatively simple stimuli (e.g., digits, letters, colors, etc.). Principles derived from this research have been used as the basis for developing theories about complex processing (e.g., LaBerge & Samuels, 1974; Shiffrin & Schneider, 1977). In the present paper we examine how well the major phenomena in simple visual search generalize to searching for words and categories. Our purpose is two-fold. First, we want to test the generalizability of the simple search results. We hope to show that searching for letters, words, categories, or superordinate categories involves the same information processing mechanisms. Our second purpose is to test the existence of general principles which we feel can become the basis for postulates of complex processing theories. In particular, we wish to show that consistent practice can develop automatic component processes (see below) which can be cascaded to perform complex information processing activities.

Schneider & Shiffrin (1977; Shiffrin & Schneider, 1977) have identified two major classes of visual search effects. The classes of effects are based on 1) the relationship between the target and distractor set and 2) the amount of practice. The first class, varied mapping (VM) effects, occurs when subjects can not consistently respond to stimuli across trials. For example, a particular stimulus which was responded to as a target on one trial might on the next trial be a distractor. Hence, the subject's response to a given stimulus is varied across trials. The other class, consistent mapping (CM) effects, occurs when subjects receive extensive training and can respond to stimuli consistently across trials (e.g., whenever a given stimulus occurs it is always attended and responded to and never ignored). Schneider and Shiffrin (1977) resolved many conflicts in the visual search and memory scanning literature by showing that some researchers were employing VM paradigms and others were examining data from CM paradigms. For example, linear set-size effects are typically observed from research using VM procedures, while flat or non-linear set-size functions are observed in CM paradigms.

Schneider and Shiffrin found qualitative as well as quantitative differences between VM and CM search performance. They interpreted these differences as indicative of the presence of two qualitatively distinct forms of information processing. The processing that occurs in VM paradigms is referred to as control processing. Control processing is characterized as slow, serial, effortful, and capacity limited (see Shiffrin & Schneider, 1977). Control processes are under direct subject control and are used to deal with novel or inconsistent information. Asymptotic control processing performance is achieved with little training. The processing occurring in CM paradigms is referred to as automatic processing. Automatic processing is characterized as fast, parallel, fairly effortless processing that is not limited by short-term memory capacity. Automatic processes allow performance of well developed skilled behaviors and require extensive training to develop.

Automatic/control processing theory (Schneider, Dumais, & Shiffrin, in press; Shiffrin & Schneider, 1977; Schneider & Fisk, Note 1) suggests that automatic processes can be cascaded indefinitely to perform complex processing activities. The theory proposes that fully developed automatic processing is not limited by short-term memory and does not reduce capacity limited control processing resources. It is also assumed that automatic component processes can be cascaded, building a chain of any number of consistent operations. The processing chain could process stimuli without reducing limited control processing resources. Hence, an automatically processed visual stimulus should be analyzed as features, letters, a word, a semantic concept, a category, a superordinate category, etc., without reducing limited attentional resources. However, if at any stage the processing is not consistent, limited control processing resources will be required.

For the remainder of the introduction we will discuss seven issues that have been prominent in the attention literature and provide principles which should be identifiable in complex search. These issues have formed the core around which the perceptual level experiments have evolved. The experiments will examine the first six issues. These phenomena are grouped as VM effects (issues 1-3) and CM effects (issues 4-7).

<u>Varied Mapping Effects</u>

1. <u>Linear set-size effect</u>. Results from the now classic Sternberg (1966) memory scanning paradigm and visual search paradigm (e.g., Atkinson, Holmgren, & Juola, 1969) indicate that reaction time performance is a linear function of memory set size (i.e., the number of items in memory to be compared). Depending on the stimuli, comparison times can range from approximately 30 msec for digit stimuli to approximately 100 msec for random forms (Cavanagh, 1972). The linearity of the function relating response latency to the size of the memory set suggests a serial succession of comparisons between the memory and probe stimuli.

2. <u>Serial exhaustive versus serial self-terminating search</u>. Sternberg (1966, 1969, 1975) found a linear set-size effect in which the slope of the positive (target present) and negative (target absent) responses were equal. These data led Sternberg to suggest a serial exhaustive search model where the probe input item is compared serially to all memory set items, even if the match occurred with the first comparison. Sternberg proposed a comparison process in which memory items are serially compared with all the stimuli. After all the comparisons are completed, the decision stage executes a response indicating the presence or absence of any match. This model predicts the linear, parallel set-size functions found by Sternberg.

In contrast to exhaustive search, a serial self-terminating model assumes that the search process is terminated whenever a match between a memory set item and a probe item occurs. This model predicts that the comparison slopes for positive trials should be one-half those for negative trials. Generally, when the experimental situation does not contain trials requiring long reaction times (e.g., greater than 800 msec) the subjects will be biased toward an exhaustive process (see Schneider & Shiffrin, 1977, Experiment 2, p. 31-32). Self-terminating search is typically employed when reaction times are long. The data seem to indicate that an exhaustive search process is used in experimental situations with short reaction times because, on the average, this strategy yields shorter response latencies (see Sternberg, 1969, for a further discussion of this issue).

3. Effect of comparison load. Data presented by Briggs and Johnsen (1973) and Schneider and Shiffrin (1977) clearly indicate that estimates of comparison slopes must include both the memory set size and the test (or probe) frame size (i.e., number of items on the test probe trial). Their data show that reaction time is an increasing function of the product of memory set size and test frame size.

Consistent Mapping Effects

4. Practice affects performance. When subjects receive extensive practice at consistently dealing with stimuli (i.e., CM training) their performance and search processes undergo quantitative and qualitative changes. For example, after receiving CM practice, Neisser's (Neisser, Novick, & Logan, 1963) subjects could perform the visual search task six times faster than before practice. Schneider and Shiffrin reported a comparison slope 25 times faster in CM trained conditions than in VM trained conditions. It is important to note that these substantial performance changes do not occur with VM practice even if thousands of trials of VM training are provided (see Kristofferson, 1972a; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

5. Reduced comparison slopes. If subjects receive sufficient CM practice, the comparison slope estimate can drop to effectively zero (Schneider & Shiffrin, 1977). Other studies have shown that with extended CM practice the set size function is non-linear and tends toward zero (e.g., Briggs & Johnsen, 1973; Kristofferson, 1972b; Swanson & Briggs, 1969). The implication of these results is that the search proceeds in parallel and has little or no dependence on short term memory capacity.

6. Reduction in effort (resource cost). Recently, evidence has been presented that indicates that processing CM trained stimuli requires no measurable cost in terms of control processing resources. More specifically, CM stimuli can be processed without requiring control processing resources or decreasing processing capacity available for other processes (Logan, 1978, 1979; Schneider & Fisk, Note 1).

7. Failure of focused attention. As subjects receive CM training, they have difficulty ignoring trained stimuli even when told explicitly to do so. Eriksen and Eriksen (1974) demonstrated subjects' reaction time slowed when irrelevant flanking stimuli were presented in a choice reaction time task. Ostrey, Moray, and Marks (1976) also presented data that show the interference effects from CM trained stimuli. Shiffrin and Schneider (1977, Experiment 4a) found that subjects could not ignore CM trained stimuli but could easily ignore VM trained stimuli.

In order to test the above issues, the following experiments examined these phenomena using word and category search. Experiments 1 and 2 were similar to a standard Sternberg task. The subjects were presented with a memory set of 1, 2, 3, or 4 items and required to quickly determine if a memory set item matched one of two items on the subsequent test frame (frame size was 2). The memory set items could be either words (each from a different taxonomic category) or taxonomic category labels. Word and category search conditions were manipulated between trial blocks. On word search trials, the subjects responded positively (with a button push) if a word in the test frame matched a memory set word. If no match was found they responded by pushing a different button. During category search trials the subjects responded positively if a word in the test frame was an exemplar from a category name in the memory set. Otherwise, they pushed another button indicating neither of the words in the test frame was an exemplar from the categories in the memory set. In Experiment 3 the subjects were required to perform a digit span task while simultaneously performing either CM or VM category search.

The first experiment examines the issues (1-3) related to VM search processes; that is, it examines set size effects, type of search termination, and load effects. The second experiment investigates the effects of extensive CM training on category and word search comparison slopes (issues 4 and 5). The final experiment explores the effort or resource costs associated with CM and VM search processes (issue 6). Evidence already exists to support issue 7 that there is a failure of focused attention with category search and this will be reviewed in the general discussion.

Experiment 1 -- VM Search

The first experiment examined VM set-size effects, type of search termination, and load effects when subjects perform word and category search. Previous word and category search experiments have not examined performance after extensive VM practice. Since visual search research has been conducted utilizing large amounts of training with variably mapped letters (e.g., Kristofferson, 1972a; Schneider & Shiffrin, 1977) that condition was not included in the present experimental series. The first experiment, then, is a replication of previous VM category and word search experiments (see Juola and Atkinson, 1971; Juola and McDermott, 1976; McFarland, Kellas, Klueger, and Juola, 1974); however, subjects in the present experiment received much more category search practice than the subjects in previous experiments.

Method

Procedure. The subjects performed a task that was very similar to the task used by Sternberg (1966). The subjects were required to memorize a list of one to four items. These memory set items could be words (e.g., Lime, Foot, Hill) or taxonomic category labels (e.g., Fruit, Weapon, Color). Words and category labels were never mixed within a memory set. After the subject committed the memory set to memory (unlimited study time was provided), he/she initiated the trial with a button push. Thereafter a fixation dot was presented for 500 msec followed by the probe (or test frame) display. The probe was displayed for a maximum of four seconds or until the subject's response. The probe display consisted of two words presented one above and one below the central fixation dot. The two probe words on the display were both either four or five letter words. To illustrate, on a positive, memory set size three, category trial, the subject would see the category labels Fruit, Weapon, Color, push the initiation button, see the focus dot, then the words Shirt and Rifle, and respond by pushing the "target present" button. Subjects rested their right index finger above two response buttons. They pressed one button if a memory set item (a category exemplar in category search trials) was present in the probe display, otherwise they pushed the other button. The subjects were encouraged to respond quickly but to keep error rates low.

The subjects were provided with three performance feedback cues. 1) On correct responses, a random dot pattern would appear to spin off the screen from the target's display location (positive trials) or from the fixation dot (negative trials). 2) Error feedback consisted of a tone burst given through the subject's headset and the display of the actual target word (positive trials) or a line of dots (negative trials). 3) During training the subjects were also provided an indication of their cumulative accuracy during training. The feedback procedure was used to facilitate motivated performance over the thousands of trials in this and the following experiment.

The subjects were run in groups of two or three. Each subject's display was independent of the others. Subjects participated in two 45 minute sessions per day and completed both the training and experimental trials in 22 sessions.

The subjects also participated in a short subsidiary experiment which examined the load effect. In this experiment the probe frame consisted of only one word. The subsidiary experiment was the same as the main experiment in all other ways. For this subsidiary experiment, all subjects completed 30 blocks of trials in two sessions.

Stimuli. The categories and the words making up the categories were chosen from the category norms of Battig and Montague (1969). Each category contained eight exemplars, four four-letter and four five-letter words. All but 2 words had a high ranking in the Battig and Montague norms. The overall mean ranking of the words was 8.8 with a standard deviation of 6.1. The categories actually used were: Fruits, Articles of clothing, Weapons, Parts of a building, Musical instruments, Natural earth formations, and Colors. For half of the subjects their set contained Human body parts and for the other half the set contained Four-footed animals. The letters making up the words were upper case and were constructed from dots on a rectangular grid 32 dots wide by 48 dots high. The characters subtended .43 degrees in width and .62 degrees in height. The refresh rate of the dots making up the stimuli was 10 msec. The room was dimly lit (.4 foot candles incidental light) with the dots easily visible on the display (.005 foot lamberts per dot). The subjects sat 46 cm from the display. In a given word, each letter was separated by .3 cm (.37 degree visual angle). The four and five letter words were 2.4 and 3 cm in length (2.9 and 3.7 degrees visual angle), respectively. The distance from the central fixation dot to each word was .75 cm (.93 degree visual angle).

Design. The relationship between the target and distractor set was varied in its mapping. In this VM procedure the target and distractor words were chosen from the same set, that is, a word could be a target on one trial and a distractor on the next. The memory set size (one through four) was manipulated between trials. The probability of a target occurring in the test frame was .5 and positive/negative trials were randomly varied between trials. The search condition, either category or word search, was manipulated between blocks of trials. Each trial block was 48 trials in length. The subjects completed 100 blocks in eight sessions. All experimental manipulations were within subjects.

Training. Prior to participating in the experiment, the subjects received 11,340 trials of practice in pilot experiments. This practice consisted of 9540 trials of category search. The category search practice consisted of: 8460 trials of memory set size one; 1080 trials where the memory set size varied between one and three; 7425 trials were VM category practice and 2115 trials were CM category practice. There were 1800 trials of word search where the memory set size varied between one and three. The subjects completed all training in 14 sessions.

Equipment. The experiment was computer controlled. The computer was programmed to present the appropriate stimuli, collect responses, and control timing of the display presentation. The stimuli were presented on Tektronix Model 604 and 620 cathode ray scopes which contained P-31 phosphors. Each subject wore a headset through which white noise and the error tone were carried.

Subjects. Six University of Illinois students (3 males) were paid for their participation. All were right handed, had normal or corrected to normal vision, and reported English as their native language.

Results and Discussion

The relevant data from this experiment are presented in Figures 1 (left panel) and 2. Figure 1 shows the average reaction time for correct trials (last 10 trial blocks). (Note: memory set size 1, 2, 3, and 4 equals 2, 4, 6, and 8 comparisons, respectively.) Error rates for category search averaged .05 and .02 for positive and negative trials, respectively. The error rates ranged from .02 to .08 for category positive search trials and from .01 to .03 for negative category search trials. Word search error rates averaged .03 and .01 for positive and negative trials, respectively. The word search error rates ranged from .01 to .04 for positive trials and from .01 to .03 for negative trials. Figure 2 presents slope data for both category and word search as a function of practice. Each point on the graph is the average of 10 blocks.

Insert Figures 1 and 2 about here

The data presented in Figure 1 (left panel) show linear set-size effects for both category and word search. The correlations between memory set-size and RT were .99 in all cases for the first and last group of 10 blocks. The linear set-size effect was consistent across all subjects.

The negative and positive slopes in both the category and word search condition were not parallel, suggesting at least some self-termination (see Figure 1). None of the subjects produced parallel positive and negative slopes. Initially, the ratio of negative trial to positive trial word search slopes was 1.86 (84 and 45 msec, respectively). For the final 10 groups of blocks this ratio was 1.45 (68 and 47 msec, respectively).

Positive word search slopes were stable across replications [$F(9,45) < 1$], and negative word search slopes dropped from 84 to 68 msec [$F(9,45)=6.72$]. There was no change in the word search slope for the last 40 trial blocks.

The category search slopes clearly indicate self-terminating search with stable slopes after the sixth replication. The initial negative to positive slope ratio (i.e., first 10 groups of blocks) was 2.45 (273 msec and 111 msec, respectively). This ratio reduced to 2.19 by the last group of 10 blocks (slopes of 202 and 92, respectively). After the first 10 blocks there was little change in the slope ratio ranging from 2.02 to 2.22. The positive trial category slopes dropped significantly [$F(9,45)=2.50$] during training from 118 msec (first 20 trial blocks) to 91 msec (last 20 trial blocks). Negative trial slopes also significantly decreased [$F(9,45)=6.72$] from 267 msec (first 20 blocks) to 196 msec (last 20 blocks). In the last 40 trial blocks there were no significant differences due to practice.

The individual subject's data for the first 60 trial blocks were less stable for category search than word search primarily because the subjects' error rates fluctuated. However, the last 40 trial blocks produced stable individual subject data as their error rates stabilized.

The data from the subsidiary experiment that utilized a probe frame size of one (i.e., 1, 2, 3, or 4 comparisons) produced data similar to the main experiment. The set size function was linear for both category and word search. The ratio of negative to positive slopes was somewhat reduced being 1.5 (175 msec and 117 msec) and 1.3 (52 msec and 40 msec) for category and word search respectively. These data replicate two phenomena in the letter search literature. First the data replicate the Schneider and Shiffrin (1977, Experiment 2) result that reaction time is an increasing function of the number of comparisons required (or load) whether memory set size or probe frame size is increased. Second, they show that increasing memory load while holding the total number of comparisons constant slows reaction time. Comparing the results from frame size 2 and 1 with an equal number of total comparisons (e.g., $M=2$, $F=1$ versus $M=1$, $F=2$), shows that increasing memory set size slowed reaction time an average of 7 msec and 62 msec in the word and category search conditions. These results are compatible with the letter search results showing additional time is used in search for every additional memory set item (see Schneider & Shiffrin, 1977, p. 27).

The present results are consistent with the Juola and Atkinson (1971) and Juola and McDermott (1976) finding that category search is slower than word search. Those two studies, however, found evidence for exhaustive search in both category and word search. The positive trial slopes of those two studies were very similar to those presently reported (see Juola and McDermott, 1976, p. 571); however, their negative trial slopes were about half those reported here. McFarland et al. (1974) did find evidence for some self-termination search in category search (see general discussion for interpretation of when self-termination occurs).

In summary, the present data provide strong support for the generality of previous experimental results that have examined VM search issues with less complex stimuli. We have found that up to and including category search the function relating reaction time to number of comparisons is linear and suggestive of a serial self-terminating search process for long reaction time conditions. The implications of this generality for complex cognitive processes will be examined in the General Discussion.

<u>Experiment 2 - CM Search</u>

The next experiment examines the effects of extensive CM training on category and word search. Schneider and Shiffrin (1977) found substantial quantitative and qualitative changes in search performance associated with CM training. Not only did they find that the processing of the CM trained stimuli increased in speed, they also found that the slopes were effectively reduced to zero. The next experiment examines whether similar reductions occur with more complex word and category search.

Method

The procedure, design, and subjects were the same as the previous experiment except that there was a consistent relationship between the target and distractor stimuli. That is, words (and therefore category structures) used as targets never occurred as distractors and vice versa.

Training. After Experiment 1 was completed, subjects received CM training on four taxonomic categories. These categories were: Four-footed animals, Human body parts, Fruits, and Furniture. One category had previously received CM training and two categories were previous VM categories (in other experiments). The Furniture category was a new category. As in the previous experiment, each category consisted of four four-letter and four five-letter words. There were 8160 trials of CM training given to the subjects (2040 trials per category). The distractor category words were all other categories that had been used as VM categories; all were high probability associates. During training, memory set size was always one category to facilitate the development of automatic processing.

At the completion of training, single category mean reaction times ranged, across categories, from 528 to 586 msec for positive trials, and 547 to 614 msec negative trials. The training required nine 45-minute sessions to complete.

Following the training, subjects participated in the variable memory set size experiment. This experiment utilized the same procedure as Experiment 1. The subjects completed 70 trial blocks (3360 total trials) in about four sessions.

Results and Discussion

The relevant data from this experiment are provided in Figures 1 (right panel) and 3. Figure 3 presents the comparison slopes (in msecs) for all conditions as a function of practice. Each data point represents the average of 10 trial blocks. In Figure 1 (right panel), mean reaction times for correct trials (last 10 trial blocks) are plotted as a function of number of required comparisons (memory set size times two). Error rates ranged from 0-2% with no relationship to the number of comparisons. The reaction time data for Experiment 1 and 2 are graphed on the same scale to facilitate comparisons between the two experiments.

Insert Figure 3 about here

Clearly, the CM training led to a reduction in slopes for both the category and word search conditions. Performance in category search improved significantly (positive category $F(6,30)=4.32$, negative category $F(6,30)=7.78$) during the experiment with the comparison slope effectively being zero (1.7 msec) for positive trials. Negative trial category search produced a slope of 10 msec. The positive/negative slope difference probably reflects a "rechecking" process on negative trials. Accuracy was substantially better in this experiment; the error rate was reduced to about half that of Experiment 1.

Word search comparison slopes were 19 msec for both positive and negative trials. There was no effect of practice on the positive word slope ($F < 1$), but there was significant improvement [$F(6,30)=2.71$] in the negative slopes. Although the CM word search slopes were substantially reduced when compared to their VM counterparts (Experiment 1), it is somewhat surprising that the CM category slopes were less than the word search slopes. In the word comparison condition, RT's were fairly fast, hence subjects would not be encouraged to develop automatic processing in word condition.[1] The subjects were biased toward category search during training. Had we eliminated this bias by training the word and category search between subjects, we believe the word search slopes would also be close to zero.

As can be seen in Figure 1 (right panel), there is <u>no linear set-size effect</u> for positive trial category search (correlation = .29). Negative trial category search produced a correlation between RT and load of .93. This correlation was .97 and .99 for word search positive and negative trials, respectively.

Comparison of the left and right panels in Figure 1 reveals the <u>substantial decrease in processing time</u> required to make a correct decision after CM training. For example, CM category search reaction times were 614 and 1223 msec faster than VM category search for positive and negative trials (eight comparisons), respectively. For word search, the VM and CM differences were 153 and 291 msec (eight comparisons) for positive and negative trials, respectively. In all cases the decrease in RT was not due to an increase in error rates.

The CM practice did produce <u>qualitative performance changes</u> such as reduced slope, reduced linearity of the set-size effect, and the ratio of negative to positive slopes. These changes did not occur with VM training (i.e, in Experiment 1).

We believe the present results suggest subjects were doing category search as opposed to word search in the CM category search condition. In the CM category condition, subjects had to learn to detect 32 words (eight words in four categories) but only eight words in the word search condition. By the fourth group of blocks in Figure 3, each CM word in the word condition was detected more times than the words in the CM category condition (including training), but the CM word search slopes were still higher than the category slopes. Also in the CM category condition, subjects were never informed as to what words to search for and hence they could not search for [illegible] of particular words. In current experiments we are more directly testing the presence of category search by examining category training transfer to non-trained category words.[2]

In summary, the data from Experiment 2 provide strong support for the generality of CM search effects previously reported in the literature. The CM training effects reported by Schneider & Shiffrin (1977) are not limited to paradigms using simple stimuli. It could be argued that the subjects in the present experiment were simply learning to respond to the physical structure of the words and that the "processing" was still primarily at the perceptual level. Although we would not want to argue that no learning of the physical features was taking place (and facilitating performance), it seems that a simple physical matching model cannot account for the category search performance. If subjects were responding solely on the basis of a physical match then it seems that the word search performance should have maintained its superiority over category search at all comparison levels. In fact, with eight comparisons, category search was faster (21 msec) and less error prone (.02 compared to .04) than word search.

Experiment 3 -- Category Search Resource Cost

The final experiment examines the resource costs of VM and CM category search. This experiment examines whether previous results of developing costless perceptual detection processes generalize to category search. Specifically, does VM category search require processing capacity, and is CM category search effectively resource cost free? With the completion of this experiment, the components necessary for the discussion of a general theory of the development of complex cognitive skills will be in place.

In order to measure the resource sensitivity of category search, subjects participated in a dual task experiment. The subjects were required to perform a serial recall digit span task (the primary task) concurrently with VM or CM category search (the secondary task). They also performed single task versions of the digit and the search tasks. The subjects were required to maintain performance equivalent to their single task level on the primary task during the dual task trials.

Method

Subjects. Five of the subjects who had participated in the previous experiments were employed in the current experiment. Four subjects participated in Part 1 of the experiment and five subjects participated in Part 2.

Trial Sequence & Procedure. The first display of each trial indicated the experimental condition and the subject's digit serial recall accuracy (except for single task category search conditions). This display, which was terminated by a button push, was followed by a 500 msec presentation of a fixation dot. Thereafter, a series of eight frames was presented. There were two different ways in which the frames were constructed. 1) For the first part of the experiment, each frame consisted of a word and a digit. The word was presented in the middle of the screen with the digit presented directly above or below the word. The digit location alternated on a frame by frame basis. The presentation of a four or a five letter word was also alternated every other frame. The time from the onset of one frame to the onset of the next was 1.6 sec. The 1.6 second frame time was used because with shorter frame times subjects could not maintain reasonable accuracy on the digit serial recall task. At these frame times subjects were expected to produce near ceiling performance in the single task search conditions. 2) Part 2 of the experiment contained frames composed of two words with a digit presented between the words. The words were presented one above the other and were both either four or five letter words. The number of letters per word alternated on a frame by frame basis. The frames were presented for 1.6 sec.

Except for single task category search conditions, the subjects' primary task was to remember the digits in their correct order (serial recall). At the end of each trial (i.e., sequence of eight frames) the subjects recalled the digits by pushing numbered buttons on the response box. The subjects were not time pressured when recalling the digits; they were given up to 3.5 seconds to enter each digit.

For the secondary task, subjects were required to detect exemplars from the target category or categories (indicated by the search condition). A single button was to be pushed whenever a target category exemplar was detected.

Design. There were five different search conditions with the search condition being manipulated between blocks. There were three single task conditions: 1) digit task; 2) CM search; and 3) VM search. There were two dual task conditions: 1) digit task/CM category search; 2) digit task/VM category search. During CM category search trials, the subjects were required to search for exemplars from any of the four previously trained CM categories. VM search conditions required subjects to search for exemplars from one or two previously trained VM categories. For the first half of the experiment (Part 1), the VM memory set size was always one category. During the second half of the experiment the memory set size was either one or two categories (manipulated between blocks).

In all search conditions exemplars from the target category(s) could occur either 0, 1, or 2 times per trial; each trial consisted of a sequence of eight frames. Target frequency was manipulated between trials, with each frequency occurring on 33 percent of the trials. Trial blocks were 30 trials in length.

The subjects completed four replications of the 5 conditions in the first part of the experiment. Part 1 required six 40 minute sessions to complete. The second part of the experiment consisted of two replications of the five conditions followed by the completion of two blocks of VM with memory set size of 2 categories (both single and dual task conditions). Part 2 required four sessions to complete. The stimuli and equipment were the same as described in the previous experiments.

Results and Discussion

The results of Experiment 3 are presented in Figures 4 and 5. Briefly, these data show that, after some dual task experience, subjects were able to concurrently perform the digit task and the CM category detection task as well as they could perform each task singly. However, VM category detection performance declined substantially when that task was performed with the digit task.

Insert Figures 4 and 5 about here

Digit recall, Part 1. Average serial recall performance is presented in Figure 4. As can be seen in that figure, single task digit recall performance did not show significant improvement with practice between replications one and four [$F(1,3)=7.53$, $p>.05$]. However, dual task digit recall performance between replications one and four did show improvement over replications in both CM [$F(1,3)=53.1$] and VM [$F(1,3)=80.7$] category search dual task conditions. This improvement was from 5.18 to 6.45 and 5.0 to 6.63, respectively. By the fourth replication (270 trials of digit recall experience) the subjects were able to perform the digit recall task concurrently with CM or VM category search at a level equivalent to single task digit recall performance. That is, by replication 4 the subjects were able to protect their primary task performance.

Category search detection accuracy, Part 1. During the first replications, there was a 10 percent drop in dual CM detection accuracy (when compared to single CM detection performance). By the fourth replication the difference between CM single and dual detection accuracy was only 3 percent (CM single, .98 versus CM dual, .95). The VM dual detection accuracy declined by about 25 percent over the single task accuracy and was fairly stable across the four replications. On the fourth replication the VM single detection accuracy was .99 and VM dual task detection accuracy was .76.

Part 2 data. The results from this half of the experiment are quite similar to the first half data. Digit recall was stable across single and dual conditions at 6.67, 6.68, 6.79, and 6.37 for digit only, CM dual, VM dual (one category), and VM dual (two categories), respectively. Figure 5 presents the detection accuracy for Part 2. CM dual search performance declined by 2%. VM dual search performance declined 26% for one category search ($M=1$) and 43% for two category search ($M=2$).

Summary, Parts 1 & 2. Subjects could classify each word as to its membership (or lack of membership) in the four CM categories as accurately in dual task situations as when they performed only the CM search task. In particular, subjects could carry on a digit span task and simultaneously determine whether each of 16 words (part 2) were members of the categories four-footed animals, human body parts, fruits and furniture without measurable deficit in either the digit span or detection task. It should be noted that this is an extremely difficult task. Early in practice subjects clearly indicated that they did not think they could ever do both tasks simultaneously without deficit.

It is possible that with other measures of cost, the present automatic categorization would not be cost free. Subjects only had to categorize two words every 1.6 seconds and were performing near ceiling in the single task categorization conditions. The serial digit recall task and categorization task overlapped only in the encoding stage. Past research has shown that automatic detection of a target does briefly (e.g., 200 msec) interfere with simultaneous search processing (Shiffrin & Schneider, 1977, Experiment 4d). The present results suggest that if such interference was occurring it was brief enough not to influence the digit encoding and short-term memory maintenance. In pilot experiments we found digit serial recall declined when digits were presented with shorter frame times than 1.6 seconds. Hence, we feel subjects did not have excess time in the serial digit recall task.

The data clearly show that subjects can perform an automatic categorization task at least at the rate of two words every 1.6 seconds without a deficit in concurrent digit span performance. The high performance in automatic detection with control processing resources allocated to another task parallels the Schneider and Fisk (Note 1) result that shows automatic and control search can be combined without deficit in detection performance. Note, this is not to imply that in some situations control processing resources might not improve performance on an automatic task (see Discussion and Schneider & Fisk, Note 1) but that accurate automatic processing is possible with little or no control processing resources.

In the VM category condition, subjects could not perform simultaneous word and category search without deficit. Subjects' dual task VM detection accuracy dropped severely (compared to VM single task performance) even though subjects were comparing words to only a single category (e.g., clothing). When the number of VM category classifications was doubled (from one to two), the single to dual task VM deficit also almost doubled (from 26 to 43 percent deficit, Part 2). In both CM and VM dual task trials, subjects were able to protect their primary task performance. Therefore, the difference in CM and VM dual task ability cannot be attributed to bias or differential task emphasis.

These results suggest that subjects may require some dual task time sharing experience before joint automatic and control processing can be combined without deficit. In the present experiment there was a need for some time sharing training (three sessions) before CM single and dual task performance was equivalent. This is similar to previous letter search results that indicate subjects typically require several sessions of training before joint automatic and control processing can be combined without cost (see Discussion and Schneider & Fisk, Note 1).

General Discussion

The present results suggest that there are no qualitative differences between searching for letters, words, or categories. In fact, with the exception that word and category VM slopes are slower, the present category search results are equivalent to the letter search results of Schneider and Shiffrin (1977, Experiment 2).

The VM results show a linear set-size effect. The linear regression of number of comparisons to reaction time slope accounted for 99% of the variance in both word and category search. The only difference between the letter, word, and category results is that category search is possibly slower. The positive response slope (Experiment 1, replication 10) was 47 msec for words and 92 msec for categories. This compares with the 23 msec slope observed by Schneider and Shiffrin (1977, Experiment 2) for letter search. We doubt that the present slower slope is due to dealing with word or category information but is instead a function of the uncertainty of the comparison process and inter-item confusability. Cavanagh (1972) has reviewed results showing simple stimuli comparison slopes ranging from 30 to 100 msec. The uncertainty in the category condition results from each category having eight exemplars of varying similarity to the other categories. We feel that letter search slope would substantially increase in letter search conditions if each letter could be presented in one of eight different fonts.

The VM word and category termination results are similar to those of letter search. Initially (in Experiment 1), both word and category search negative to positive search ratios were 1.86 and 2.43. These ratios are in the range of the 2 to 1 ratio interpreted as indicating self-terminating search (see Sternberg, 1969). With extended training, the word search slope ratio reduced to 1.45 suggesting that at times some subjects might be performing an exhaustive search. The category slope ratio remained above 2 to 1 throughout the experiment suggesting subjects continued a self-termination comparison process. We feel the differences in word versus category search are due to subjects adopting a self-terminating strategy when responses get very long (greater than 800 msec). The memory slope ratio that Schneider and Shiffrin (1977, Experiment 2) observed for letter search with frame size 1 was 1.43, whereas with frame size 2 where reaction times exceeded 800 msec, the slope ratio was 1.93.

The comparison load effects for word and category VM search were analogous to letter search results (Briggs & Johnsen, 1973; Schneider & Shiffrin, 1977). Reaction time was a function of the product of the number of comparisons [i.e., memory set-size (M) X test frame size (F)]. In previous VM letter search (see Schneider & Shiffrin, 1977, p. 15), and the present word and category VM search, increasing the memory set size while keeping the total number of comparisons constant resulted in increasing reaction time (e.g., in category search M=2, F=2, positive RT was 82 msec faster than M=4, F=1 positive RT).

The practice effects of category and word search show minor VM improvements. In the present VM conditions there was no change in positive trial word slope and a 22% reduction in category slope. We interpret the reduction in VM category slope as due to initial unfamiliarity of searching for the exemplars of the categories used in the experiment. After subject error rates stabilized (first 60 trial blocks, Experiment 1) there was little change in VM category slope. The VM practice improvements are similar to those found when subjects are searching for novel characters (LaBerge, 1973). The relatively large and rapid CM practice effects for word and category search are analogous to CM character search results (see Shiffrin & Schneider, 1977).

The present reduced CM comparison slopes are similar to the previous character search results. In previous character (Schneider & Shiffrin, 1977, F=2) and the present word and category search, the CM comparison times were 10, 18, and 2 msec, respectively. The previous character and present category search reaction time to number of comparisons functions were highly non-linear. The CM word search functions in the present experiment were linear. However, we observed similar linear CM character search functions when subjects are not pressured to respond quickly (see Discussion, Experiment 2).

The reduction in effort in CM category search parallels the costless CM character search results. Schneider and Fisk (Note 1) found no dual task deficit when subjects had to perform simultaneous CM and VM character search with emphasis on the VM task. Experiment 3 showed no dual task deficit for simultaneous CM category search with emphasized digit span task. The digit span task would be classified as a control process task (see Shiffrin & Schneider, 1977, p. 156) and should show effects comparable to VM search. It is certainly possible that with other measures of cost, automatic categorization would be degraded (see Schneider & Fisk, Note 1). However, the present procedures show quite complex processing can be done without measurable costs in short term memory and detection procedures. In both Schneider and Fisk (Note 1) and the present experiment several sessions of dual task experience were necessary before both tasks could be done without cost. The Schneider and Fisk (Note 1) dual VM search results and the present VM category with digit span results show substantial dual task deficits when combining two control processes even after extensive practice.

The last issue in the search literature, failure of focusing attention, was not examined in the present results. However the previous literature already shows the parallels between letter, word, and category search. Eriksen and Eriksen (1974) demonstrated interference effects of irrelevant flanking letters. Shaffer and Laberge (1979) showed a similar effect with words and semantic categories. Ostrey, Moray, and Marks (1976) showed subjects could not ignore CM letters or words from a specified CM semantic category.

Principles for Human Information Processing

The generality of search results provides basic principles for human information processing. The principles can provide guidelines for theorizing about complex information processing.

Principle 1 -- Performance is determined more by processing mode than by stimulus complexity. The CM results of letter and category search show much greater similarity than do the CM and VM letter search results. This indicates that the processing mode (i.e., automatic versus control) plays a much more important role in determining performance than does the complexity or depth of processing (e.g., character versus category search).

Principle 2 -- Substantial performance improvement occurs primarily when subjects can consistently process the information. VM search conditions show little or no performance improvement with practice at searching for familiar targets. The present CM comparison slope reduced 98% in the category search condition. Schneider and Fisk (in press) have found that the less consistent the processing the less total improvement there is with practice and the sooner performance asymptotes. These results suggest the skill improves by developing automatic component processes which consistently process information.[3]

Principle 3 -- Automatic processes can be cascaded to perform complex operations with no observable cost. In dual CM category search and digit-span task, the stimuli were processed into features, letters, words, and semantic categories with no observable cost in digit-span. This supports the proposal of Shiffrin and Schneider (1977, p. 160) that stimuli can activate a chain of automatic processes without reducing control processing resources. This principle is important because it indicates there is no upper bound of the complexity of an automatic processing sequence (see Schneider & Fisk, Note 1, for discussion). If new automatic component processes can be executed at no cost then there is no limit to the number of automatic stages through which a stimulus could be processed.

Principle 4 -- Processing complexity will be limited by the components of the task which require control processing. This is a corollary to the assumption that automatic processes are fast and not capacity limited and that control processes are slow and capacity limited. The extent to which a task utilizes control processing resources limits processing complexity. Arbitrarily categorizing a few symbols (e.g., VM search), or updating memory (e.g., running a paired-associate task), or simply maintaining a set of elements in memory (e.g., digit span), can exceed human capacity. However, classifying chess board patterns in terms of a dozen moves which fall into consistent exchange patterns may not (e.g., Newell & Simon, 1972).

The results and principles discussed above provide support for automatic/control processing theory (Shiffrin & Schneider, 1977; Schneider, Dumais, & Shiffrin, in press). In fact, all the above principles can be derived from the assumptions of automatic and control processing theory (see Shiffrin & Schneider, 1977, pp. 159-171).

The above principles also provide support for production systems simulation models of human information processing (Newell, 1973, 1980). These models also provide evidence of the processing power of systems operating by the above principles. There are many variants of production system models (see Anderson, 1976), but all seem to share a common set of basic assumptions. The following discussion is intended only as a brief overview of production system concepts (for detailed accounts see Anderson, 1976; Newell, 1980). Production systems are condition-action rules. When the conditions of a production are met, the production action takes place either modifying short-term memory or performing a physical act. The production systems are contained in long-term memory and are accessed in parallel. There is no capacity limit either in the number of productions to be held in memory or the speed of access. However, all production system outputs have to be stored in short-term memory. Since short-term memory is severely limited (typically only seven units), processing complexity is limited by the short-term memory requirements and the range of productions available. Productions may activate a sequence of productions utilizing only a small portion of short-term memory. With sufficient practice, productions are assumed to be "compiled" (see Anzai & Simon, 1979; Anderson, Note 2) making them faster and reducing memory requirements. In addition, productions can be combined. Thus, multiple productions which might require substantial short-term memory capacity (for interim results) are reduced to a single production without the use of short-term memory. The ability of productions to influence behavior is generally determined by the consistency with which the application of a rule results in a positive event (e.g., see Anderson & Kline, 1979; Anzai & Simon, 1979).

The four principles discussed above support the underlying assumptions of production system modeling. Assumptions that complexity is limited by the set of available productions and short-term memory requirements are supported by principles 1 (i.e., importance of processing mode over stimulus complexity) and 4 (i.e., processing complexity is limited by use of control processing resources). The assumption that productions can be compiled and combined so they do not consume short-term storage capacity is in agreement with principle 3 (i.e., automatic processes can be cascaded at no cost). The importance of consistency in the development of new productions is similar to principle 2 (i.e., substantial performance improvement occurs only when subjects can consistently deal with information).

The success in predicting complex human behaviors by production system simulations indicates the processing power of systems constrained by the four principles above. Production system simulations have performed speech comprehension (Newell, 1980), categorization (Anderson & Klein, 1979), problem solving (e.g., Anderson, Note 4), and text comprehension (Thibodeau & Just, Note 5). A processing system which has a severely limited short-term store but can develop and execute an unlimited number of component processes (e.g., productions) to perform consistent information processing, is capable of performing complex information processing tasks.

The present experiments have shown that humans are capable of complex automatic categorization. The existence of complex automatic categorization has certain implications. Experiment 2 demonstrated that subjects could detect the occurrence of unrelated semantic categories independent of the number of categories searched for. Experiment 3 showed that this detection process occurred without reducing resources for a short-term memory task. Such automatic detection may be critical in detecting infrequent but important complex situations. To illustrate, consider the detection of emergencies while piloting an aircraft. First, the routine aircraft control tasks are often sufficiently demanding to consume control processing resources and prohibit control process checking of possible emergency conditions. Second, many events would be classified as an emergency and these do not fall into a simple superordinate category. Our results suggest that had each class of emergency event been consistently attended to in the past, automatic processes would have developed to attract attention to those events. The events would attract attention independent of the allocation of control processing resources at the time of the event. Thus, whenever any member of any previously attended to class of events occurred, attention would be drawn to that event. We are carrying out additional research to specify how training on a subset of elements transfers to automatic processing of other members of the set.

The presence of an automatic costless categorization process may be important to interpreting linguistic and semantic analysis. In parsing a sentence the incoming stream of words must be categorized into the appropriate parts of speech, consuming little if any attentional resources. Many semantic comprehension tasks require a quick scanning of previous input. For example, one component of resolving pronoun reference is scanning the previous text for semantic nodes which match the semantic characteristics of the pronoun (Kintsch & Van Dijk, 1978). Experiment 3 showed the control process search for a single well defined and practiced category dropped 26% when subjects were under high concurrent short-term memory load. Detection accuracy for two categories dropped 43%. To enable accurate resolution of pronoun referents, we would expect that subjects must learn to automatically categorize incoming word strings into the appropriate pronoun referents.

The lack of control of automatic categorizations may strongly bias perceptions. In person perception, past experience at consistently categorizing particular features (e.g., dress, age, race) with certain traits (e.g., sloppiness) could develop an automatic categorization process. If automatic, the categorizations would take place without the observer intentionally classifying the individual. In fact, these classifications would be difficult to inhibit. The literature on "snap judgements" (Schneider, Hastorf, & Ellsworth, 1979) indicates observers make fast unconscious categorizations of persons met the first time. Present research in cognitive attribution analysis of stereotyping suggests that such uncontrolled habitual classifications can have a strong influence on behavior (Hamilton, 1979).

At present we have only begun to understand complex search and the implications of the principles of its operation. The present results are encouraging, particularly in terms of the generality of previous search results.

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Footnotes

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1 In CM letter search experiments we occasionally find subjects who do not improve with practice and continue to show performance common to VM search. Typically when we require subjects to respond more quickly, their performance improves substantially and shows the fast accurate responding seen by most subjects in CM search. The results suggest the slow responding subjects do a control process check even when the automatic process output is reliable. In the present experiment control process checks of the category search conditions would double reaction times where as checks in the word conditions would only slow them by about 30%. Had we pressured subjects to minimize word search reaction times we feel less checking would have occurred and the slopes would have been reduced and non-linear.

2 Experiments currently being conducted indicate that the development rate of automatic category detection is independent of category size (category size being 4, 8, and 12 exemplars). These experiments also show a high degree of transfer to untrained exemplars of CM trained categories.

3 Defining what is "consistent" is still problematic. Fisk and Schneider (Note 3) have shown that automatic component processes develop to consistent components of the task, even when the processing from stimulus to response is not consistent.

Figure Captions

Figure 1. Experiments 1 (VM) and 2 (CM) search reaction time as a function of the memory set size with frame size 2 for the last 10 blocks.

Figure 2. Experiment 1 comparison slope as a function practice. Each point represents 240 trials per subject.

Figure 3. Experiment 2 CM learning. Each point represents 240 observations per subject.

Figure 4. Experiment 3, part 1, digit recall as a function of condition and practice. Each replication represents 30 trials per subject per condition.

Figure 5. Experiment 3, part 2, category search detection performance with two words presented every 1.6 seconds.

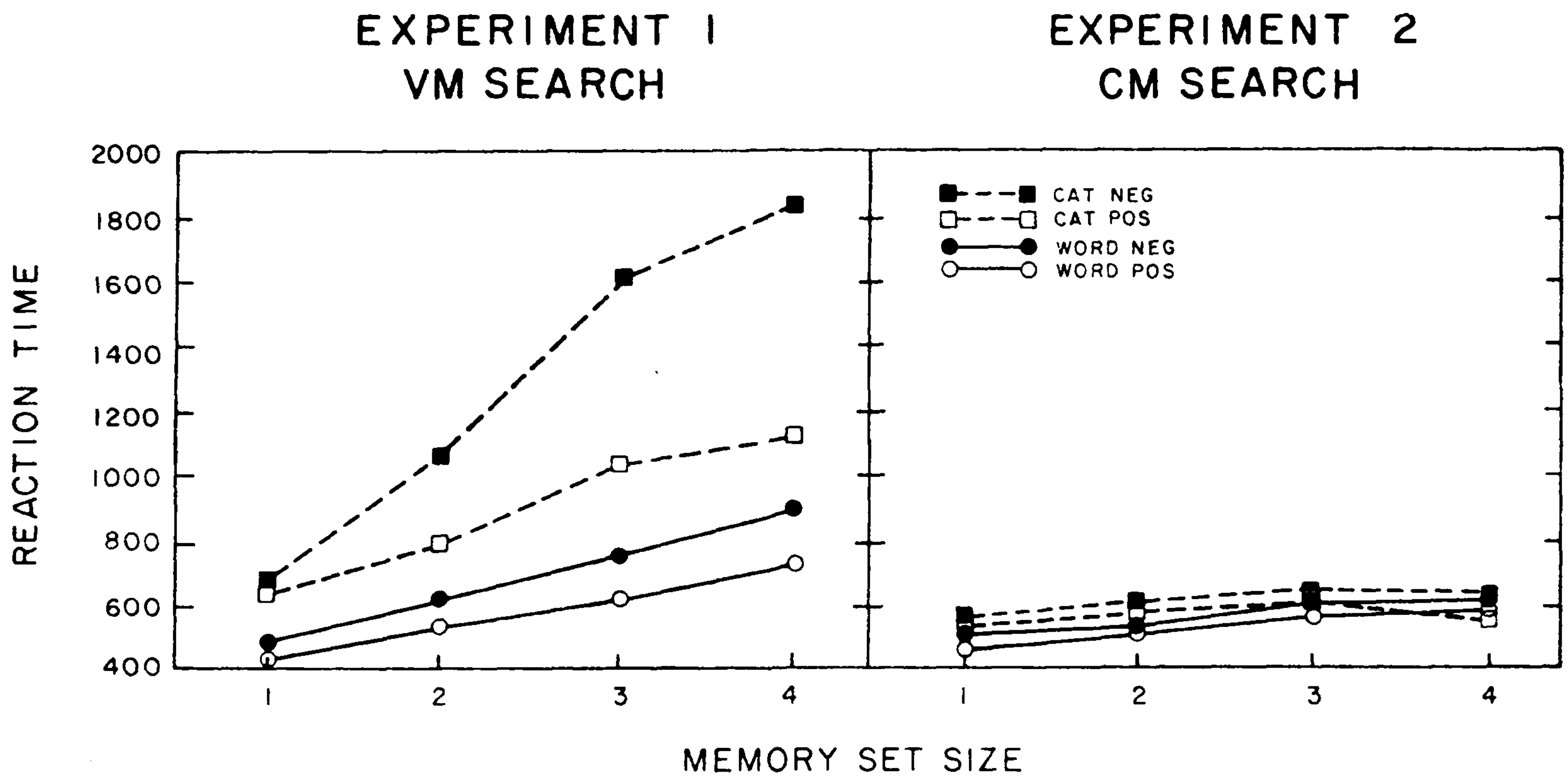

Figure 1. Experiments 1 (VM) and 2 (CM) search reaction time as a function of the memory set size with frame size 2 for the last 10 blocks.

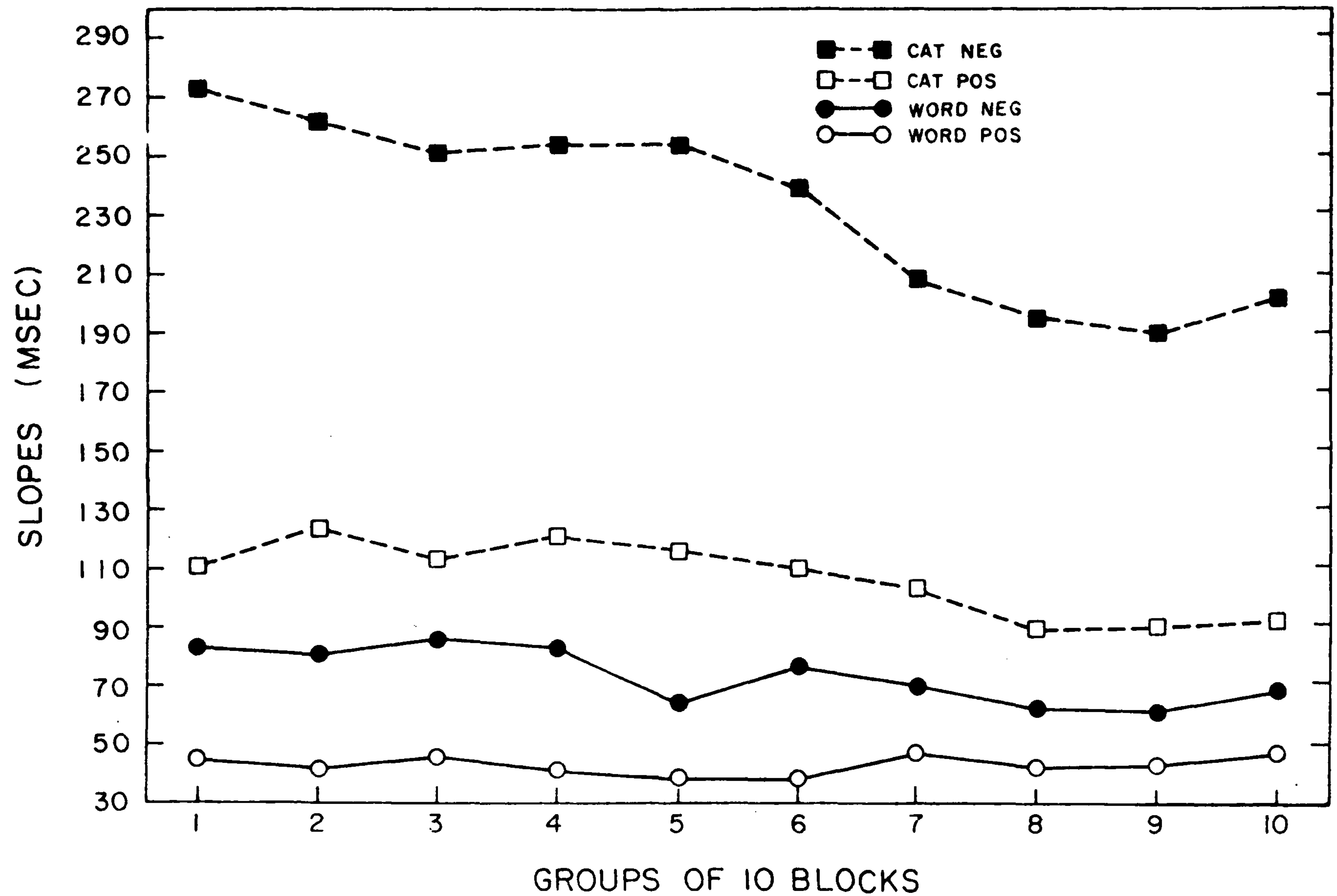

Figure 2. Experiment 1 comparison slope as a function of practice. Each point represents 240 trials per subject.

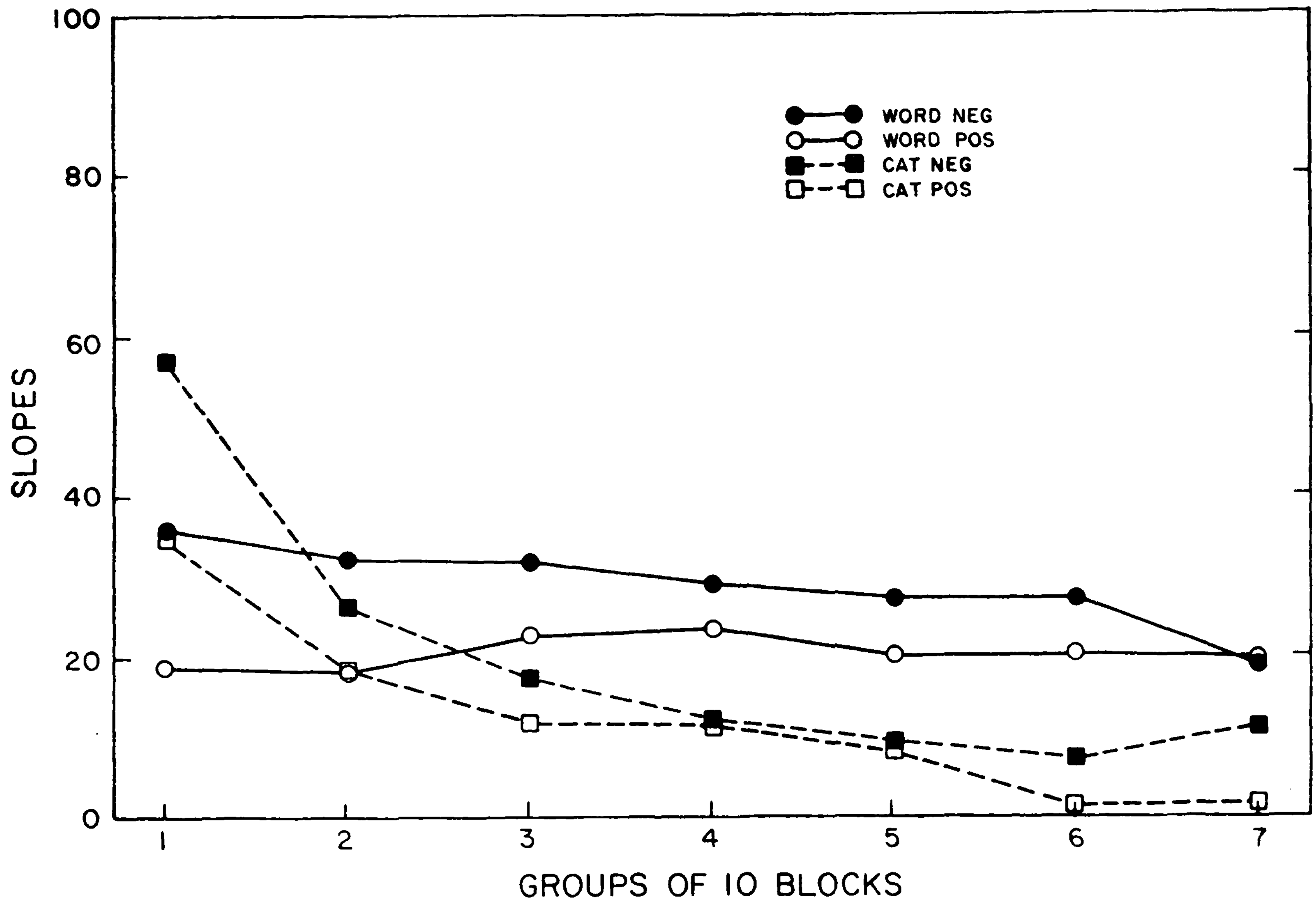

Figure 3. Experiment 2 CM learning. Each point represents 240 observations per subject.

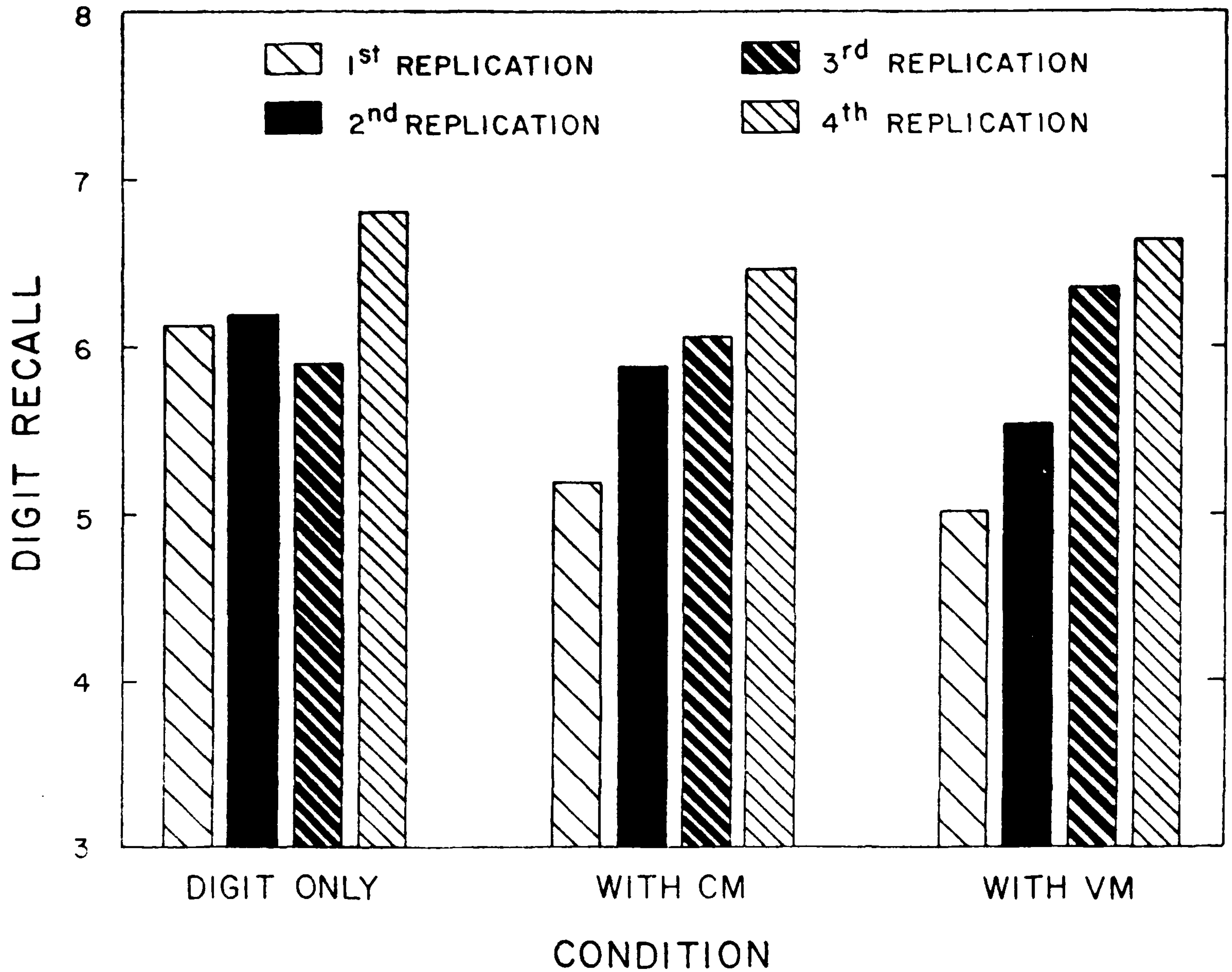

Figure 4. Experiment 3, part 1, digit recall as a function of condition and practice. Each replication represents 30 trials per subject per condition.

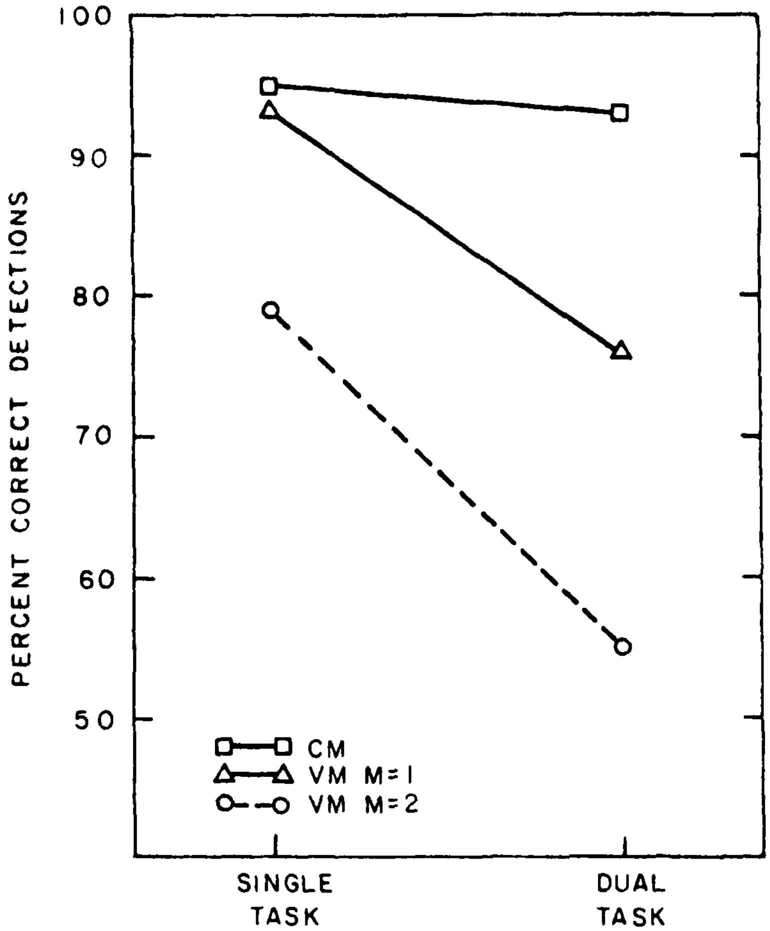

Figure 5. Experiment 3, part 2, category search detection performance with two words presented every 1.6 seconds.

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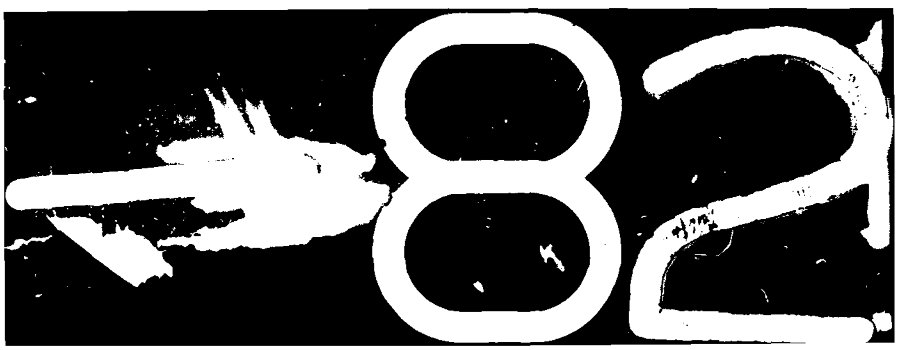
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